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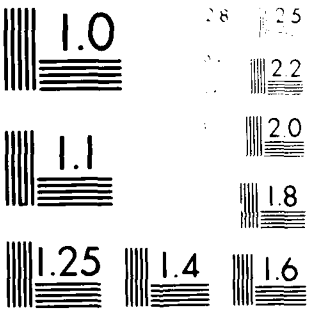
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August 1981

GRAY CODES WITH EQUAL BIT-ERROR PROBABILITIES

Jacques E. Ludman
John L. Sampson

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
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It is often desirable to use Gray codes with properties different f se of the standard binary reflected code. Previously, only short codes (3 256-element) could be systematically generated or found with a given set of properties. This report describes a technique where long codes (65,000-element or longer) as well as short codes can be systematically generated with desired properties. The technique is described and demonstrated by generating codes of various lengths with the desired property of equal column change counts. Several examples of the use of the technique for generating codes with

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other desired properties are outlined.

Preface

The original idea that Gray code sequences can be moved to alter the nature of a Gray code comes from Jerry Silverman, RADC/ESE, who noted that in a Gray code path (not cycle), the last pair could usually (not always) be inserted elsewhere in the code. If a place for the pair could not be found, the last group of 4 or 6 could be checked and an insertion point found for it.

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Gray Codes With Equal Bit-Error Probabilities

1. INTRODUCTION

Gray codes[1] are used extensively in a variety of applications, such as shaft encoding or analog-to-digital conversions to minimize the effects of ambiguous analog signals near boundaries.[2] The codes are used also in the design of experiments[3,4] to minimize parameter changes. Perhaps the most important application is the use of Gray codes in phase-shift-keyed (PSK) communications. For these applications, it is important to be able to generate Gray codes with particular characteristics. One extremely important set of Gray codes is the one with equal numbers of changes in each column of bits. This set has equal bit-error probabilities in PSK communications. Examples of members of this set for 3 bits to 16 bits are given in Tables 1 through 14.

The technique developed here to generate these codes is based on the symmetry properties of the binary reflected code (BRC)[5-7] and the transformation of the BRC in accordance with simple rules. Codes up to 12-bit (4096-element) are readily transformed with pencil and paper, whereas larger codes, up to 20-bit (1,048 576-element), can be transformed with the aid of a computer.

(Received for publication 24 August 1981)

(Cited references are listed on page 80.)

2. THEORY

The fundamental property of a Gray code is that when expressed in binary form every element differs from each of its neighbors in one bit only. Since each element has N bits, it has N potential neighbors. Two of those neighbors will be the actual neighbors; the others will be located elsewhere in the code. The fundamental feature of the code transformation is that the sequence of elements between a given element and one of its potential neighbors can be removed, leaving the remaining sequence still a Gray code. If new neighbors for the removed sequence can be found adjacent to each other, the sequence may be inserted between them, resulting in a new Gray code containing all the elements of the original code but in a different order and thus with different properties.

The symmetry of the BRC is such that removable sequences and their insertion points are easily located and the effects of moving such sequences are predictable. Figure 1 may be used to show how this is done in the simple case of a 4-bit BRC. A boundary, called the half-boundary, has been marked halfway down the code, between elements 8 and 9. The entire portion of the code above this boundary is "reflected" below it, the elements, in reverse order, differing from their counterparts above only in the leftmost bit, which will be referred to as bit number 1. Thus the reflection of element 2 (0001) is element 15 (1001). Similarly, the *quarter-boundaries and eighth-boundaries* are indicated, reflecting the element with changes in bit number 2 and bit number 3, respectively. Binary reflected codes are always circuits; element 1 may be considered adjacent to element 16.

In Figure 1, it may be seen that element 4, in addition to its neighbors 3 and 5, has two potential neighbors 1 and 13, which are its reflections across the adjacent eighth-boundary and the half-boundary, respectively. Since elements 1 and 4 are potential neighbors, it is clear that elements 2 and 3 could be removed and that the remainder would still be a Gray code. Now it may be seen that elements 2 and 3 have as potential neighbors their reflection across the half-boundary, elements 15 and 14. The removed sequence, 2, 3 could therefore be inserted (in reverse order) between elements 14 and 15, resulting in a new Gray code containing all the elements of the original BRC. If the changes in each column of bits in Figure 1 are counted, the difference between the two codes becomes apparent: the BRC has 2 changes in column 1 (leftmost), 2 in column 2, 4 in column 3, and 8 in column 4. After transformation the column change count pattern has changed from 2, 2, 4, 8 to 4, 2, 4, 6. (The change between the last element and the first is included in the count.)

Initial Code						Transformed Code				
Element Number	Bit #1	Bit #2	Bit #3	Bit #4	Boundaries	Element Number	Bits #1	Bits #2	Bits #3	Bits #4
1	0	0	0	0		1	0	0	0	0
2	0	0	0	1	1/8	4	0	0	1	0
3	0	0	1	1		5	0	1	1	0
4	0	0	1	0	1/4	6	0	1	1	1
5	0	1	1	0		7	0	1	0	1
6	0	1	1	1	1/8	8	0	1	0	0
7	0	1	0	1		9	1	1	0	0
8	0	1	0	0	1/2	10	1	1	0	1
9	1	1	0	0		11	1	1	1	1
10	1	1	0	1	1/8	12	1	1	1	0
11	1	1	1	1		13	1	0	1	0
12	1	1	1	0	1/4	14	1	0	1	1
13	1	0	1	0		3	0	0	1	1
14	1	0	1	1	1/8	2	0	0	0	1
15	1	0	0	1		15	1	0	0	1
16	1	0	0	0		16	1	0	0	0
No. of Changes	2	2	4	8		No. of Changes	4	2	4	6

Figure 1. Four-bit Binary Reflected Gray Code With Reflection Boundaries Indicated. Elements 2 and 3 can be inserted between elements 14 and 15 without destroying the Gray code property.

4. MOVEMENT OF PAIRS

The [illegible] (removal and insertion elsewhere) that can be made is that of [illegible] such as the one just described. This move, labeled "A" [illegible] pair, labeled "B", are illustrated in Figure 2. (Note that only pairs [illegible] can move.) It has already been seen that the move of [illegible] will alter the distribution of changes in the columns, and that move A, of a [illegible] across a [illegible] boundary, results in adding two changes to column 1 and subtracting two from column [illegible]. Examination of move B shows that it results in adding two changes to column [illegible] and subtracting two from column 4. The effect of moving a pair in an N-bit code across a $1/2^K$ boundary (for K = 1, half boundary; K = 2, quarter boundary, etc.) is [illegible] the move increases the change count in column K by 2 and decreases by 2 the count in column N. Later it will be [illegible] this is a special case of a set of more general rules.

In order to facilitate the explanation of more complicated movements of pairs or longer sequences, the process will be described as a pair (or sequence) moving between the [illegible] of another pair as being "eaten" by that pair. The fact that a pair has eaten another pair (or a sequence) does not prevent the eating pair from moving, and does not change the effect of such a move. A sequence that has been eaten is simply carried along in the move of the pair that has eaten it. The change count is not affected by the presence of the sequence that is carried along. In the example (Figure 2), if move A alone is made, the new order of element numbers is

1, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14, 3, 2, 15, 16.

Move B alone results in

1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 14, 11, 12, 13, 16.

Move A followed by move B results in

1, 4, 5, 6, 7, 8, 9, 10, 15, 2, 3, 14, 11, 12, 13, 16.

The column change count after both moves is 4, 4, 4, 4. There may be more than one way to reach a particular distribution of column changes; for example, 4, 4, 4, 4 may equally well be achieved if 4, 5 eat 12, 13 and 2, 3 eat 6, 7. The resulting Gray codes, of course, are not the same.

	Initial Code					Transformed Code				
Element Number	Bits #1	#2	#3	#4	Boundaries	Element Number	#1	#2	#3	#4
1	0	0	0	0		1	0	0	0	0
2	0	0	0	1		4	0	0	1	0
3	0	0	1	1		5	0	1	1	0
4	0	0	1	0		6	0	1	1	1
5	0	1	1	0		7	0	1	0	1
6	0	1	1	1		8	0	1	0	0
7	0	1	0	1		9	1	1	0	0
8	0	1	0	0	1/2	10	1	1	0	1
9	1	1	0	0		15	1	0	0	1
10	1	1	0	1		2	0	0	0	1
11	1	1	1	1		3	0	0	1	1
12	1	1	1	0	1/4	14	1	0	1	1
13	1	0	1	0		11	1	1	1	1
14	1	0	1	1		12	1	1	1	0
15	1	0	0	1		13	1	0	1	0
16	1	0	0	0		16	1	0	0	0
No. of Changes	2	2	4	8		No. of Changes	4	4	4	4

Figure 2. Four-bit BRC Transformed With Two Moves, A and B, That Preserve the Gray Code Property

4. MOVEMENT OF LONGER SEQUENCES

Moving pairs can reduce the column change count only in the Nth column of an N-bit code. In order to reduce the count in other columns, longer sequences must be moved. They turn out to be of length 4, 8, 16, and so on. A sequence of four may be moved if all the bits in the next-to-last (N-1) column are alike. A sequence of eight must have like bits in column N-2, and so on. *Figure 3 shows a 5-bit* (32-element) BRC with a column change count of 2, 2, 4, 8, 16. Move A carries a sequence of eight across the half-boundary. In order to remain a Gray code, elements 8 and 9 must be matched with 25 and 24 respectively; this requires that the sequence of eight be inverted by halves, placing its last four elements before its first four. The order that results is

1, 2, 3, 4, 5, 6, 7, 8, 25, 26, 27, 28, 21, 22, 23, 24, 9, 10 . . .

Two changes have been subtracted from column 3 and added to column 1. Examination of the effects of moves such as this one leads to the formulation of two rules:

Rule 1. If a sequence of $2^{(P+1)}$ elements is moved, where P is any integer between zero and N-3, the number of changes in column N-P is reduced by 2.

Rule 2. If a sequence (of any size) is moved across a $(1/2)^K$ boundary, the number of changes in column K is increased by 2.

There are some restrictions on the movement of sequences:

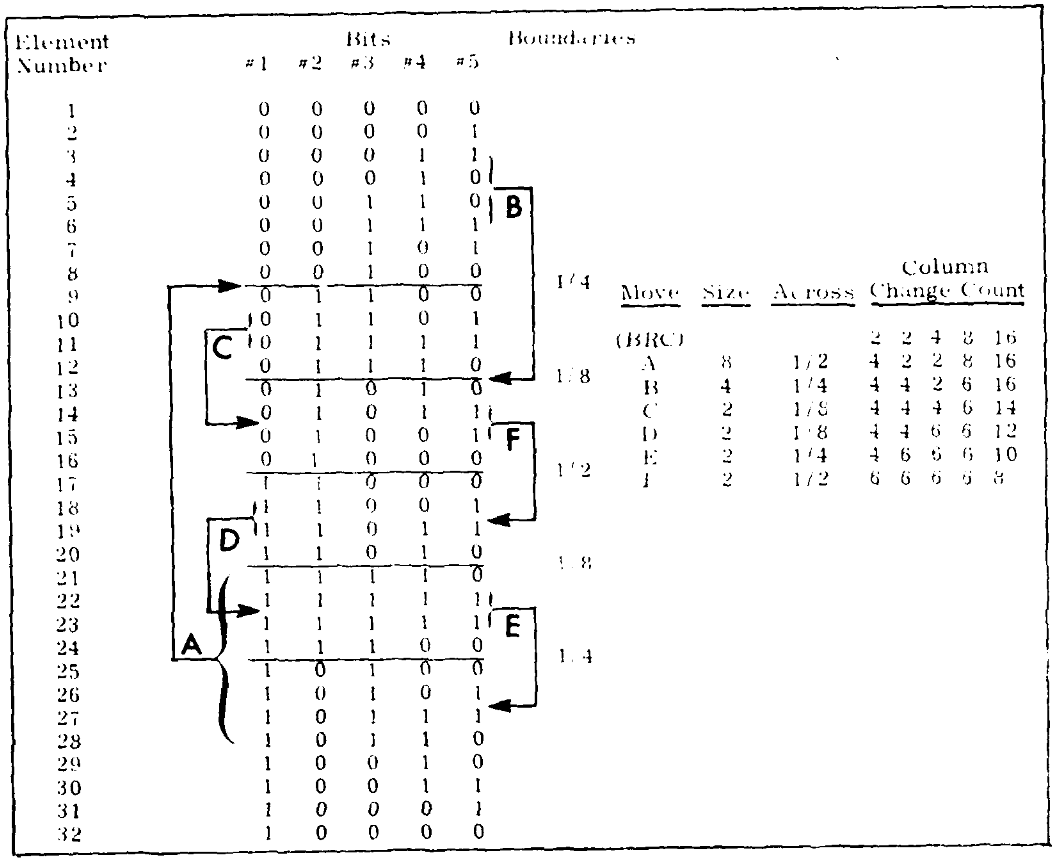
Rule 3. A sequence of $2^{(P+1)}$ elements must have like bits in all elements in its N-P column.

Rule 4. A sequence may be moved and eaten only once (see Rule 6).

Rule 5. A pair may eat only once.

Rule 6. A pair may eat a sequence that includes other eaten sequences; no chain of moves, however, may result in a pair ultimately eating itself.

Rule 7. After a sequence has moved, adjacent elements usually cannot move. (For example, after move A in Figure 3, elements 20 and 29 are fixed.) An exception to this rule will be seen shortly.



Element Number	Bits #1	#2	#3	#4	#5	Boundaries
1	0	0	0	0	0	
2	0	0	0	0	1	
3	0	0	0	1	1	
4	0	0	0	1	0	
5	0	0	1	1	0	
6	0	0	1	1	1	
7	0	0	1	0	1	
8	0	0	1	0	0	
9	0	1	1	0	0	1/4
10	0	1	1	0	1	
11	0	1	1	1	1	
12	0	1	1	1	0	
13	0	1	0	1	0	1/8
14	0	1	0	1	1	
15	0	1	0	0	1	
16	0	1	0	0	0	
17	1	1	0	0	0	1/2
18	1	1	0	0	1	
19	1	1	0	1	1	
20	1	1	0	1	0	
21	1	1	1	1	0	1/8
22	1	1	1	1	1	
23	1	1	1	1	1	
24	1	1	1	0	0	
25	1	0	1	0	0	1/4
26	1	0	1	0	1	
27	1	0	1	1	1	
28	1	0	1	1	0	
29	1	0	0	1	0	
30	1	0	0	1	1	
31	1	0	0	0	1	
32	1	0	0	0	0	

Move	Size	Across	Column Change Count				
(BRC)			2	2	4	8	16
A	8	1/2	4	2	2	8	16
B	4	1/4	4	4	2	6	16
C	2	1/8	4	4	4	6	14
D	2	1/8	4	4	6	6	12
E	2	1/4	4	6	6	6	10
F	2	1/2	6	6	6	6	8

Figure 3. A 5-bit BRC. Letters A through F indicate a set of 6 moves leading to a column change count of 6, 6, 6, 6, 8

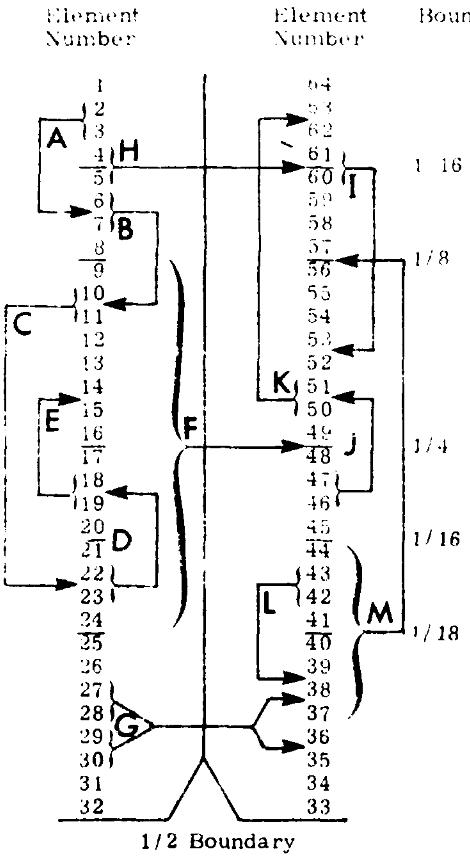
In Figure 3, move A separates elements 24 and 25 making them ineligible for further moves as a pair, but leaves pairs 22, 23 and 26, 27 still movable. Move B takes a sequence of four across a quarter-boundary. An inversion by halves is again necessary, leading to the order:

. . . 10, 11, 12, 5, 6, 3, 4, 13, 14 . . .

By rules 1 and 2, the count in column 4 goes down 2 and that in column 2 goes up 2.

After moves A and B, other moves may be made to complete the transformation of the BRC into a Gray code with, *for example*, an equal distribution of column changes. The length of the sequence determines the column whose count is decreased (Rule 1); the boundary across which the sequence moves determines the column whose count is increased (Rule 2). This type of move is all that is necessary for most of the desired distributions. There are several other allowed moves which are useful in the remaining cases.

A pair through which a higher-symmetry (lower K) boundary passes may move after both of its lower-symmetry neighboring pairs (through which a lower-symmetry boundary passes) have moved. This is an exception to Rule 7. The move labeled "F" in Figure 4 is an example of such a higher-symmetry move. The requirements for such a move are that both neighboring pairs have previously moved (moves D and E in Figure 4) and that the next-nearest neighbors be in place (elements 1 and 8 in Figure 4). The effect of such a move increases the column count as before, but the column decreased by two is column N-1 rather than column N. A still higher-symmetry move can be made if exactly three pairs of elements have been moved from each side of a given element. The count decrease here is in column N-2 and for higher-symmetry moves in correspondingly lower columns.



Move	Size	Across	Column Change Count					
(BRC)			2	2	4	8	16	32
F	16	1/2	4	2	2	8	16	32
M	8	1/4	4	4	2	6	16	32
G	4(Split)	1/2	8	4	2	6	4	40
H	2(Hi Sym)	1/2	10	4	2	6	12	30
C, E, J	2	1/4	10	10	2	6	12	24
B, I, K, L	2	1/8	10	10	10	6	12	16
A, D	2	1/16	10	10	10	10	12	12

Figure 4. A Variety of Moves Leading to a 6-bit Gray Code With a Column Change Count of 10, 10, 10, 10, 12, 12. The lower half of the code has been folded upward for convenience, and the listing of bits omitted

Sequences of four or more need not be placed between the same elements but may be split up in a variety of ways; for example, the 3, 4, 5, 6 sequence of four may split into 3, 4 entering 13, 14 and 5, 6 entering 11, 12. This decreases column N-1 by two and N by two, and increases column 1 by four.

Tables 1 through 14 list the transition sequences for 3-bit through 16-bit Gray codes with equal bit-error probabilities. Each number in a table identifies the bit that changes between elements.[2] These codes were generated from the BRC using the moves thus far described. Figure 4 shows all of the foregoing moves used to generate a 10, 10, 10, 10, 12, 12 distributed code (N = 6), with the final sequence of BRC numbers

1, 8, 25, 26, 31, 32, 33, 34, 35, 30, 29, 36, 45, 48, 17, 20, 21, 24, 9, 12, 13, 14,
19, 22, 11, 6, 3, 2, 7, 10, 23, 18, 15, 16, 49, 52, 61, 4, 5, 60, 53, 54, 55, 56,
41, 44, 37, 28, 27, 38, 43, 42, 39, 40, 57, 58, 59, 62, 51, 46, 47, 50, 63, 64.

5. GENERAL MOVES

The moves noted in the previous sections are sufficient to change the BRC to another Gray code with any desired column change count. They are well-suited to the task because each move reduces the change count in one column and increases it in another in a thoroughly predictable way. For other purposes, there is a still more general class of moves which is useful and which includes these moves as a subset.

Symmetrically centered about every reflection boundary are a number of sequences that can be moved. In the 5-bit case already examined (Figure 3), for example, the quarter-boundary between 8 and 9 is a reflection boundary for sequences 8-9, 7-10, and 5-12 (of lengths 2, 4, and 8), as already noted. In addition, there are sequences 6-11, 4-13, 3-14, and 2-15 which are of length 6, 10, 12, and 14, respectively, and thus do not satisfy Rule 1. Nevertheless, they may be moved across the boundary and inserted in the proper place. Furthermore, there are other points where, with the right kind of inversion, these sequences can also be inserted.

The procedure is to locate a desired insertion point and invert the sequence by sections, breaking it at a point to match the insertion point. For example, the 6-11 sequence can be inserted between elements 24 and 25 by inverting at the symmetry point to get

. . . 24, 9, 10, 11, 6, 7, 8, 25 . . .

or can be inserted between 22 and 23 by inverting at 10, 11 to get

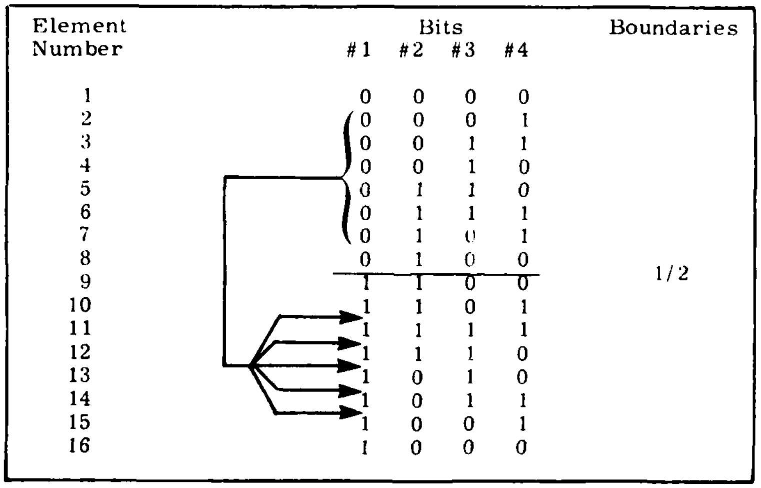
. . . 22, 11, 6, 7, 8, 9, 10, 23 . . .

In addition, long sequences may be split up into parts, which are then inserted where needed.

Moves of this type are useful in solving such problems as Gray codes with time linearity.[6] If the group of six in Figure 5 is inverted and put between 10 and 11 the order becomes

1, 8, 9, 10, 7, 2, 3, 4, 5, 6, 11, 12, 13, 14, 15, 16 .

If the pair 2, 3 then eats pair 14, 15, the result is the N = 4 minimum time linearity found by Dickinson.[3] With the use of such moves, and with an interactive computer to calculate the linearity (or some other desired property), the BRC can be readily converted.



Element Number	Bits #1	#2	#3	#4	Boundaries
1	0	0	0	0	
2	0	0	0	1	
3	0	0	1	1	
4	0	0	1	0	
5	0	1	1	0	
6	0	1	1	1	
7	0	1	0	1	
8	0	1	0	0	
9	1	1	0	0	1/2
10	1	1	0	1	
11	1	1	1	1	
12	1	1	1	0	
13	1	0	1	0	
14	1	0	1	1	
15	1	0	0	1	
16	1	0	0	0	

Figure 5. A Variety of Possible Moves for a 6-element Sequence. The final column change count depends upon where the sequence goes

6. CONCLUSIONS

The task of creating Gray codes with a given set of characteristics has been shown to be solvable by locating and removing sequences from the binary reflected Gray code and reinserting these sequences in other parts of the code. These removable sequences abound and can be readily located by symmetry. The locations for reinsertion of a sequence are numerous and also readily located by symmetry. The simple inversion of the moving sequence is obvious on comparing the sequence and the insertion point. With a little familiarity with moving sequences, it becomes easy to see how to split them up and put the pieces into various locations.

A particular subset of the allowed moves has the property of changing the column change counts in an exact way; the procedure has been given here for using that subset of moves in a straightforward way to convert the BRC to a Gray code with any desired change count distribution.

7. TRANSITION SEQUENCES FOR GRAY CODES

TABLE 1. TRANSITION SEQUENCE FOR 3-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

12131213

TABLE 2. TRANSITION SEQUENCE FOR 4-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

23241432 34131214

TABLE 3. TRANSITION SEQUENCE FOR 5-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

34243425 15251315 43234514 12131215

TABLE 4. TRANSITION SEQUENCE FOR 6-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

34352543 45242326 16261316 45436263 45461412 13251565 25651312 14121326

TABLE 5. TRANSITION SEQUENCE FOR 7-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

34353436 26454345 46243534 37172717 37175645 43727345 46571417 52571753
57252324 23261676 45254676 13162614 16261316 26151675 25761312 14121327

TABLE 6. TRANSITION SEQUENCE FOR 8-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

34385834	36343534	37343534	36343534	38182818	67564543	45465768	18281418
28183825	28657535	75682428	63682623	24232523	24232717	27131727	14172713
17271517	68657546	45482845	46457568	67131768	65754645	48284546	45756867
14176865	72756867	13176865	72756867	16121312	14121312	57828713	12142328

TABLE 7. TRANSITION SEQUENCE FOR 9-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

45464535	65456537	34353436	34353438	34353436	34353437	34353436	34353439
19291939	19291419	29193925	29392429	39262976	36792435	34372797	68565745
46454345	46454756	58679724	27976856	53565867	97252797	63679724	23262324
23252324	23281828	13182814	18281318	28151828	13182814	18281318	28161872
78131872	78141879	76267978	13187976	26797815	18797685	65256586	79781318
79768565	25658679	78141879	76856574	59496454	92945469	49547565	86797813
18797685	65745949	64549294	54694954	75658679	78171213	12141213	12152324
23261896	76267698	13189676	26769814	18929813	18929815	18929813	12142329

TABLE 8. TRANSITION SEQUENCE FOR 10-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

45464547	4546454A	8A454645	47375658	56575654	56575658	56573546	36463534
39343534	36343534	37343534	36343534	38343534	36343534	37343534	36343534
3A1A7828	7A1A7838	7A1A7828	7A141A78	287A1A78	387A1A78	287A151A	78676965
756585A2	A5856575	4947687A	1A786769	65756585	35856575	6967687A	1A786769
65756585	A4A6A4A5	A4A74A5A	4A6A4A5A	4A2A4A5A	4A6A4A5A	47A4A5A4	A6A4A585
65756967	687A141A	78676962	6967687A	1A786769	63696768	7A1A7867	69626967
687A161A	727A1A73	7A1A727A	141A727A	1A737A1A	727A151A	78769296	787A1A78
76939678	7A1A7876	9296787A	142A7876	96756585	64547454	64543454	64547454
65856576	96787A27	34353436	34353438	28382428	38252838	24283826	28382428
38252838	24283827	23242325	23242326	34353439	19291939	19291419	29193919
29151929	19391929	14192919	39192916	19291319	29141929	13192915	19291319
29141929	13192917	19828913	19828914	19828913	19828915	19828913	19828914
19828913	19828916	19828913	19828914	19828913	19828915	19828913	19828914
19828913	19828982	13121412	13121523	24231216	23242325	23242327	19A78769
67565856	A4A5A4A7	4A5A4A6A	4A5A4A2A	4A5A4A6A	4A5A47A4	A5A4A658	56576967
87A91319	A7876967	56582856	57696787	A9142325	23242326	23242325	2324232A

TABLE 9. TRANSITION SEQUENCE FOR 11-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

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45464547 45464548 45464547 45464549 45464547 45464548 45464547 4546454A
454636A6 76864686 76A63547 376A6768 67565956 57565856 57565456 57565856
57565956 5768676A 67353436 34353438 34353436 34353437 34353436 34353439
34353436 34353437 34353436 34353438 34353436 34353437 34353436 3435343B
1B897828 798B1B89 7838798B 1B897828 798B141B 89782879 8B1B8978 38798B1B
89782879 8B151B89 7828798B 1B897838 798B1B2B 141B2B1B 3B1B2B16 1B2B1B3B
1B2B142B 3B252B3B 24373435 34363435 34383435 34363435 34373435 34263435
34392939 24293925 29392429 39262939 24293925 29392429 39272939 24293925

29392429 8B879787 6A676865 75659565 75636575 65956575 68676A67 67978B89
26298B87 97838797 8B892429 8B838B89 25298B83 8B892429 8B838B89 28232427
25232423 26232429 B8797876 A6768657 56595657 56548454 64547454 64543454
64547454 64548456 57565956 57568676 A6787978 B9253437 34353436 34353437
1A2A1A3A 1A2A141A 2A1A3A1A 2A151A2A 1A3A1A2A 141A2A1A 3A1A2A16 1A3A1A3A
1A2A141A 2A1A3A1A 2A151A2A 1A3A1A2A 14149B2B 9A1A9B27 9A1A9B2B 2A171A7B
8797876A 67682867 6A678797 8B9A1A9B 9797876A 67687867 6A678797 8B9A1A9B
8797876A 67682867 6A678797 8B9A141A 9B879787 6A676818 676A6787 978B9A1A

9B879787 6A676838 676A6787 978B9A1A 9B879787 6A676828 676A6787 978B9A15
1A9B8797 876A6768 65756595 6575B2B5 75659565 7568676A 6787978B 9A131A98
8797876A 67686575 65956575 B2B57565 95657568 676A6787 978B9A14 1A2A131A
2A161A2A 131A2A14 1A2A131A 2A151A2A 131A2A14 1A2A131A 2A181A98 5B28B89A
131A98B8 28B89A14 1A98B828 B89A131A 98B828B8 9A151A98 B828B89A 131A98B8
79782879 78B89A14 1A98B879 78287978 B89A131A 98B87978 287978B6 9A161A98
B8797876 A6768657 5659565B 7B5B6B4B 5B4B8B4B 5B4B6B4B 5B4B7B45 4B6B4B5B
4B2B4B5B 4B6B454B 7B4B5B4B 6B4B5B4B 8B4B5B4B 6B5B7B56 59565756 8676A678

7978B89A 131A98B8 797876A6 76865756 59565B7B 5B6B4B5B 4B8B4B5B 4B6B4B5B
4B7B454B 6B4B5B4B 2B4B5B4B 6B454B7B 4B5B4B6B 4B5B4B8B 4B5B4B6B 5B7B5659
56575686 76A67879 78B89A14 1A929A13 1A929A15 1A929A13 1A929A14 1A929A13
1A929A17 1A929A13 1A929A14 1A929A13 1A929A15 1A929A13 1A929A14 1A929A13
1A929A16 1A929A13 1A929A14 1A929A13 1A929A15 1A929A13 1A929A14 1A929A13
1A929A19 12131214 12131215 12131214 12131216 12131214 12131215 12131214
23272324 12131215 23242326 23242325 23242328 23242325 23242326 23242325
23242327 23241AB2 BA131AB2 BA151AB2 BA131AB2 BA142326 23242325 2324232B
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TABLE 10. TRANSITION SEQUENCE FOR 12-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

45464547	45464546	45464547	45464549	45464547	45464548	45464547	4546454A
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454B
45464547	45464548	45464547	45464549	39787B4B	78793546	45473797	87B76867
69676867	565A5657	56585657	56595657	56585657	56545657	56585657	56595657
56585657	565A5657	68676967	6867B787	97353797	87B76867	69676864	68676967
6867B787	97364548	38483538	79787B4B	78797836	34353437	34353436	3435343A
34353436	34353437	34353436	34353438	34353436	34353437	34353436	34353439
34353436	34353437	34353436	34353438	34353436	34353437	34353436	3435343C

1C2C1C3C	1C2C141C	2C1C3C1C	2C151C2C	1C3C2436	34353437	34353436	34353438
34353436	34353437	34353436	34353439	34353436	34353437	34353436	34353438
34353436	34353437	34353436	3435343A	1A2A1A3A	1A2A141A	2A1A3A1A	2A151A2A
1A3A1A2A	142A3A26	2A3A242A	3A252A3A	242A3A27	2A3A242A	9C898A87	9787B768
67696768	67565A56	57565856	57565953	59565756	58565756	5A565768	67696768
67B78797	8A898C9A	252A9C89	8A879787	B7686769	67686368	67696768	67B78797
8A898C9A	242A9C89	8A879787	3787978A	898C9A26	2A9C898A	879787B6	76867696
76863686	76967686	76B78797	8A898C9A	242A9C89	8A879787	B3B78797	8A898C9A

252A9C89	8A879787	B3B78797	8A898C9A	242A9C89	8A879787	B3B78797	8A898C9A
262A939A	242A939A	252A939A	242A939A	262A939A	242A939A	252A939A	242A9C98
A879787B	76867696	76867565	A5657565	85657565	95645474	54645484	54645474
54645434	54645474	54645484	54645474	54659565	75658565	7565A565	76867696
76867B78	7978A89C	9A272A9C	98A3A89C	9A242A9C	98A3A89C	9A252A9C	98A3A89C
9A242A9C	98A3A89C	9A262A9C	98A3A89C	9A242A9C	98A3A89C	9A252A9C	98A3A89C
9A242A9C	98A3A89C	9A292324	23252324	23262324	23252324	23273435	34363435
34383435	34363435	34373435	34363435	343B1B2B	1B3B1B2B	141B2B1B	3B1B2B15

1B2B1B3B	1BAC2CAB	141BAC2C	AB1BAC3C	AB1BAC2C	AB161BAC	2CAB1BAC	3CAB1BAC
2CAB141B	AC2CAB1B	AC3CAB1B	AC2CAB15	1BAC2CAB	1BAC3CAB	1BAC2CAB	141BAC2C
AB1BAC3C	AB1BAC2C	AB171BAC	2CAB1BAC	3CAB1B2B	141B2B1B	3B1B2B15	1B2B1B3B
1B2B141B	2B1B3B1B	2B161B2B	1B3B1B2B	141B2B1B	3B1B2B15	1B2B1B3B	1B2B141B
2B1B3B1B	2B181B2B	1B3B1B2B	141B2B1B	3B1B2B15	1B2B1B3B	1B2B141B	2B1B3B1B
2B161B2B	1B3B1B2B	141B2B1B	3B1B2B15	1B2B1B3B	1B2B141B	2B1B3B1B	2B171B2B
131B2B14	1B2B131B	2B151B2B	131B2B14	1B2B131B	2B161B2B	131B2B14	1B2B131B
2B151B2B	131B2B14	1B2B131B	2B191BA9	C98A2A89	C9AB131B	A9C98A2A	89C9AB14

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1BA9C98A 2A89C9AB 131BA9C9 8A2A89C9 AB151BA9 C98A2A89 C9AB131B A9C98A2A
89C9AB14 1BA9C98A 2A89C9AB 131BA9C9 8A2A89C9 AB161BA9 C98A2A89 C9AB131B
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C9AB131B A9C98A2A 89C9AB14 1BA9C98A 2A89C9AB 131BA9C9 8A2A89C9 AB171BA9
C98A8797 87B76867 69676867 565A5657 565C8C5C 6C5C7C5C 6C5C9C5C 6C4C5C4C
7C4C5C4C 6C4C5C4C 8C4C5C4C 6C4C5C4C 7C4C5C4C 6C4C5C4C 2C4C5C4C 6C4C5C4C
7C4C5C4C 6C4C5C4C 8C4C5C4C 6C4C5C4C 7C4C5C4C 6C5C9C5C 6C5C7C5C 6C5C8C56
57565A56 57686769 676867B7 87978A89 C9AB131B A929AB14 1BA929AB 131BA929

AB151BA9 29AB131B A929AB14 1BA929AB 131BA929 AB161BA9 29AB131B A929AB14
1BA929AB 131BA929 AB151BA9 29AB131B A929AB14 1BA929AB 131BA929 AB181BA9
C898A879 787B2B78 7978A898 C9AB131B A9C898A8 79787B2B 7B7978A8 98C9AB14
1BA9C898 A879787B 2B787978 A898C9AB 131BA9C8 98A87978 7B2B7879 78A898C9
AB151BA9 C898A879 787B2B78 7978A898 C9AB131B A9C898A8 79787B67 68676967
68626867 69676867 68787978 A898C9AB 141BA9C8 98A87978 7B676867 67676867
68676967 68676B78 7978A898 C9AB131B A9C898A8 79787B67 68676967 68626867
69676867 6B787978 A898C9AB 161BA9C8 98A87978 7B787978 A898C9AB 131BA9C8

98A87978 7B787978 A898C9AB 141BA9C8 98A87978 7B787978 A898C9AB 131BA9C8
98A87978 7B768676 96768657 565A5657 56585C6C 5C7C5C6C 5C9C5C2C 5C9C5C6C
5C7C5C6C 58565756 5A565756 96769676 867B7879 78A898C9 AB151BA9 C898A879
787B7686 76967682 86769676 867B7879 78A898C9 AB131BA9 C898A879 787B7686
76967686 7565A565 756585C6 C5C7C5C6 C5C9C5C2 C5C9C5C6 C5C7C5C6 C5856575
65A56576 86769676 867B7879 78A898C9 AB141BA9 C898A879 787B7686 76967686
7565A565 7565C8C5 C6C5C7C5 C6C5C9C5 C6C4C5C4 C7C4C5C4 C6C4C5C4 C8C4C5C4
C6C4C5C4 C7C4C5C4 C6C4C5C4 C2C4C5C4 C6C4C5C4 C7C4C5C4 C6C4C5C4 C8C4C5C4

C6C4C5C4 C7C4C5C4 C6C5C9C5 C6C5C7C5 C6C5C8C5 657565A5 65768676 9676867B
787978A8 98C9AB13 1BA2AB17 1BA2AB13 1BA2AB14 1BA2AB13 1BA2AB15 1BA2AB13
1BA2AB14 1BA2AB13 1BA2AB16 1BA2AB13 1BA2AB14 12131215 12131214 1213121A
12131214 12131215 12131214 12131216 12131214 12131215 12131214 12131217
12131214 12131215 12131214 12131216 12131214 12131215 12131214 23282324
12131215 23242326 23242325 23242327 23242325 23242326 23242325 23242329
23242325 23242326 23242325 23242327 23242325 23242326 23242325 23242328
23242325 23242326 23242325 23242327 23242325 23242326 23242325 2324232C
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TABLE 11. TRANSITION SEQUENCE FOR 13-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

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45464547 45464548 45464547 45464549 45464547 45464548 45464547 4546454A
45464547 45464548 45464547 45464549 45464547 45464548 45464547 4546454B
45464547 45464548 45464547 45464549 45464547 45464548 45464547 4546454A
45464547 45464548 45464547 45464549 45464547 45464548 45464547 4546454C
45464547 45464548 45464547 45464549 45464547 45464548 45464547 4546454A
45464547 45464548 45464547 45464549 45464547 45464548 45464547 4546454B
3B898A4A 898B353B 898A4A89 8B363B89 8A4A898B 35474546 454838B8 98A87978
7C787949 787C7879 78A898B8 3538B898 A879787C 78794978 7C787978 A898B836

38B898A8 79787C78 79768676 A6768676 96768676 B6575658 56575659 56575658
5657565A 56575658 56575659 56575658 56575654 56575658 56575659 56575658
5657565A 56575658 56575659 56575658 565756B6 76867696 768676A6 76867978
7C787978 A898B835 38B89848 98B83738 B898A787 9787C787 9768676A 67686769
6768676B 4B676867 69676867 6A676867 9787C787 9787A898 B8353436 34353439
34353436 34353437 34353436 34353438 34353436 34353437 34353436 3435343A
34353436 34353437 34353436 34353438 34353436 34353437 34353436 34353439
34353436 34353437 34353436 34353438 34353436 34353437 34353436 3435343D

34353436 34353437 34353436 34353438 34353436 34353437 34353436 34353439
34353436 34353437 34353436 34353438 34353436 34353437 34353436 3435343A
34353436 34353437 34353436 34353438 34353436 34353437 34353436 34353439
34353436 34353437 34353436 34353438 34353436 34353437 34353436 3435343B
1B2B1B3B 1B2B141B 2B1B3B1B 2B151B2B 1B3B1B2B 141B2B1B 3B1B2B16 1B2B1B3B
1B2B141B 2B1B3B1B 2B151B2B 1B3B1B2B 141B2B1B 3B1B2B17 1B2B1B3B 1B2B141B
2B1B3B1B 2B151B2B 1B3B1B2B 141BAD9A 2A9DAB1B 3B1BAD9A 2A9DAB16 1BAD9A2A
9DAB1BAD 9A3A9DAB 1BAD9A2A 9DAB141B AD9A2A9D AB1BAD9A 3A9DAB1B AD9A2A9D

AB151BAD 9A2A9DAB 1BAD9A3A 9DAB1BAD 9A2A9DAB 141BAD9A 2A9DAB1B AD9A3A9D
AB1BAD9A 2A9DAB18 1BAD9A98 B898A879 787C7879 29787C78 7978A898 B89A9DAB
1BAD9A98 B898A879 787C7879 39787C78 7978A898 B89A9DAB 1BAD9A98 B898A879
787C7879 29787C78 7978A898 B89A9DAB 141BAD9A 98B898A8 79787C78 7929787C
787978A8 98B89A9D AB1BAD9A 98B898A8 79787C78 7939787C 787978A8 98B89A9D
AB1BAD9A 98B898A8 79787C78 7929787C 787978A8 98B89A9D AB151BAD 9A98B898
A879787C 78792978 7C787978 A898B89A 9DAB1BAD 9A98B898 A879787C 78793978
7C787978 A898B89A 9DAB1BAD 9A98B898 A879787C 78792978 7C787978 A898B89A
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9DAB141B AD9A98B8 98A87978 7C787929 787C7879 78A898B8 9A9DAB1B AD9A98B8
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768676A6 76867696 768676B6 57565856 57565956 57565856 57565A56 57565856
57375658 5657565A 56575658 56575659 56575658 565756B6 76867696 768676A6
76867978 7C787978 A898B89A 9DAB242B AD9A98B8 983898B8 9A9DAB25 2BAD9A98
B8983898 B89A9DAB 242BAD9A 98B89838 98B89A9D AB272BAD 9A98B898 A7879787
C7879768 676A6768 67696768 676B3B67 68676967 68676A67 68679787 C7879787
A898B89A 9DAB242B AD9A98B8 98A78797 87C78797 68676A67 68676967 68676B3B

67686769 6768676A 67686797 87C78797 87A898B8 9A9DAB25 2BAD9A93 9A9DAB24
2BAD9A93 9A9DAB26 2BAD9A93 9A9DAB24 2B3B252B 3B242B3B 292BA9D9 A939A9D9
AB242BA9 D9A939A9 D9AB252B A9D9A939 A9D9AB24 2BA3AB26 2BA3AB24 2BA3AB25
2BA3AB24 2BA3AB27 2BA3AB24 2BA3AB25 2BA3AB24 2BA3AB26 2BA3AB24 2BA3AB25
2BA3AB24 2BA3AB28 2BA3AB24 2BA3AB25 2BA3AB24 2BA3AB26 2BA3AB24 2BA3AB25
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37343534 36343534 38343534 36343534 37343534 36343534 39343534 36343534
37343534 36343534 38343534 36343534 37343534 36343534 3C1CBD9A 9B898A2A

898B9A9D BC1CBD9A 9B898A3A 898B9A9D BC1CBD9A 9B898A2A 898B9A9D BC141CBD
9A9B898A 2A898B9A 9DBC1CBD 9A9B898A 3A898B9A 9DBC1CBD 9A9B898A 2A898B9A
9DBC151C BD9A9B89 8A2A898B 9A9DBC1C BD9A9B89 8A3A898B 9A9DBC1C BD9A9B89
8A2A898B 9A9DBC14 1CBD9A9B 898A2A89 8B9A9DBC 1CBD9A9B 898A3A89 8B9A9DBC
1CBD9A9B 898A2A89 8B9A9DBC 161CBD9A 9B898A2A 898B9A9D BC1CBD9A 9B898A3A
898B9A9D BC1CBD9A 9B898A78 79787C7B 79768676 A6768676 96768676 B6575658
5D6D5D7D 5D6D5D9D 5D6D5D7D 5D6D5D8D 5D6D5D7D 5D6D5DAD 5D6D5D7D 5D6D5D8D
5D6D5D7D 4D5D4D6D 4D5D4D9D 4D5D4D6D 4D5D4D7D 4D5D4D6D 4D5D4D8D 4D5D4D6D

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4D5D4D7D 4D5D4D6D 4D5D4D9D 4D5D4D6D 4D5D4D7D 5D6D5D8D 5D6D5D7D 5D6D5DAD
5D6D5D7D 5D6D5D8D 5D6D5D7D 5D6D5D9D 5D6D5D7D 5D6D5856 5756B676 86769676
8676A676 8679787C 7879787A 898B9A9D BC141CBD 9A9B898A 7879787C 78797686
76A67686 76967686 76B65756 585D6D5D 7D5D6D5D 9D5D6D5D 7D5D6D5D 8D5D6D5D
7D5D6D5D AD5D6D5D 7D5D6D5D 8D5D6D5D 2D5D6D5D 8D5D6D5D 7D5D6D5D AD5D6D5
7D5D6D5D 8D5D6D5D 7D5D6D5D 9D5D6D5D 7D5D6D58 565756B6 76867696 768676A6
76867978 7C787979 7A898B9A 9DBC1CBD 9A9B898A 7879787  78797686 76A67686
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76967686 76B65756 58565756 59565756 58565756 5A565756 58565754 64549454
64547454 64548454 64547454 64543454 64547454 64548454 64547454 64549454
64575658 5657565A 56575658 56575659 56575658 565756B6 76867696 768676A6
76867978 7C787978 7A898B9A 9DBC1CBD 9A2A9DBC 151CBD9A 2A9DBC1C BD9A3A9D
BC1CBD9A 2A9DBC14 1CBD9A2A 9DBC1CBD 9A3A9DBC 1CBD9A2A 9DBC171C BD9A2A9D
BC1CBD9A 3A9DBC1C BD9A2A9D BC141CBD 9A2A9DBC 1CBD9A3A 9DBC1CBD 9A2A9DBC
151CBD9A 2A9DBC1C BD9A3A9D BC1CBD9A 2A9DBC14 1C2C1CBD 9A3A9DBC 1C2C161C
2C1C3C1C 2C141C2C 1C3C1C2C 151C2C1C 3C1C2C14 1C2C1C3C 1C2C181C 2C1C3C1C

2C141C2C 1C3C1C2C 151C2C1C 3C1C2C14 1C2C1C3C 1C2C161C 2C1C3C1C 2C141C2C
1C3C1C2C 151C2C1C 3C1C2C14 1C2C1C3C 1C2C171C 2C1C3C1C 2C141C2C 1C3C1C2C
151C2C1C 3C1C2C14 1C2C1C3C 1C2C161C 2C1C3C1C 2C141C2C 1C3C1C2C 151C2C1C
3C1C2C14 1C2C1C3C 1C2C191C 2C1C3C1C 2C141C2C 1C3C1C2C 151C2C1C 3C1C2C14
1C2C1C3C 1C2C161C 2C1C3C1C 2C141C2C 1C3C1C2C 151C2C1C 3C1C2C14 1C2C1C3C
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3C1C2C14 1C2C1C3C 1C2C1A1C BA2ABC1C BA3ABC1C BA2ABC14 1CBA2ABC 1CBA3ABC
1CBA2ABC 151CBA2A BC1CBA3A BC1CBA2A BC141CBA 2ABC1CBA 3ABC1CBA 2ABC161C
BA2ABC1C BA3ABC1C BA2ABC14 1CBA2ABC 131CBA2A BC151CBA 2ABC131C BA2ABC14
1CBA2ABC 131CBA2A BC171CBA 2ABC131C BA2ABC14 1CBA2ABC 131CBA2A BC151CBA
2ABC131C BA2ABC14 1CBA2ABC 131CBA2A BC161CBA 2ABC131C BA2ABC14 1CBA2ABC
131CBA2A BC151CBA 2ABC131C BA2ABC14 1CBA2ABC 131CBA2A BC181CBA 2ABC131C

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5D6D5D7D 5D6D5DAD 5D6D5D7D 5D6D5D8D 5D6D5D7D 5D6D5D9D 5D6D5D7D 56585657
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8A787978 7C787976 8676A676 86769676 8676B2B6 76867696 768676A6 76867978
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D5D4D7D4 D5D4D6D4 D5D4D9D4 D5D4D6D4 D5D4D7D5 D6D5D8D5 D6D5D7D5 D6D5DAD5
D6D5D7D5 D6D5D8D5 D6D5D7D5 D6D5D9D5 D6D5D7D5 D6D58565 756B6768 67696768
676A6768 679787C7 87978A89 8B89A9DA BC161CBA D9A98B89 8A879787 C7879297
87C78797 8A898B89 A9DABC13 12141213 12151213 12141213 12181213 12141213
12151213 12141213 12161213 12141213 12151213 12141213 27232423 25232423
26232423 25232423 2B1B2B13 1B2B141B 2B131B2B 151B2B13 1B2B141B 2B131B2B
161B2B13 1B2B141B 2B131B2B 151B2B13 1B2B141B 2B131B2B 171B2B13 12141213

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23242325 23242326 23242325 23242327 23242325 23242326 23242325 2324232C
23242325 23242326 23242325 23242327 23242325 23242326 23242325 2324232A
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23242325 23242326 23242325 23242327 23242325 23242326 23242325 2324232D
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TABLE 12. TRANSITION SEQUENCE FOR 14-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

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45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454A
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45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454D
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454A
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454B
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454A
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454C
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454A
45464547	45464548	45464547	45464549	39A9C949	C9A93539	A9C949C9	A93639A9
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7D787978	7A78797C	7B4B7879	787A7879	787D7879	8A898B89	8A9C9A9B	353B9A9C
9A898B89	8A89787D	7879787A	7879787B	4B787978	7A787978	7D78798A	898B898A
9C9A9836	3B9A9C9A	898B898A	89787D78	79787A78	79787B76	86769676	8676A676
86769676	8676C676	86769676	46769676	8676C676	86769676	8676A676	86769676
867B7879	787A787D	787D7879	8A898B89	8A9C9A9B	353B9A9C	9A898B89	8A89787D
7879767A	78797879	76867696	768676A6	76867696	768676C6	76867696	76856575
65A56575	65856575	65956575	65856575	65B56575	65856575	65956575	65856575
65A56575	65856575	65956575	65856575	65456575	65856575	65956575	65856575
65A56575	65856575	65956575	65856575	65B56575	65856575	65956575	65856575
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79787D78	798A898B	898A9C9A	9B373B9A	9C9A898B	898A848A	898B898A	9C9A9B35
3B9A9C4C	9A9B363B	9A9C4C9A	9B353438	34353436	34353437	34353436	34353439
34353436	34353437	34353436	34353438	34353436	34353437	34353436	3435343A
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8B898A9C 9A9BAEBC 1CBEAB9A 9C9A898B 898A8978 7D787978 7A787978 7B3B7879
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8676A676 86769676 867B7879 787A7879 787D7879 8A898B89 8A9C9A9B AEBC1CBE
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76967686 76C67686 76967685 657565A5 65756585 65756595 65756585 657565B5
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5E6E5E7E 5E6E5EBE 5E6E5E7E 5E6E5E8E 5E6E5E7E 5E6E5E9E 5E6E5E7E 5E6E5E8E
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67686769 676867B7 879787A7 879787D7 87978A87 8B898A9C 9A9BAEBC 1CBEAB9A
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[illegible] 1412131 1512131 141DBBA [illegible] [illegible] [illegible] [illegible]
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C2CD161D C2CD131D C2CD141D C2CD131D C2CD151D C2CD131D C2CD141D C2CD131D

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C2CD171D C2CD131D C2CD141D C2CD131D C2CD151D C2CD131D C2CD141D C2CD1326
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1CDCBEAB 9A9C2C9A 9BAEBCDC 131CDCBE AB9A9C2C 9A9BAEBC DC181CDC BEAB9A9C
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TABLE 13. TRANSITION SEQUENCE FOR 15-BIT GRAY CODE WITH UNIFORM DISTRIBUTION OF COLUMN CHANGES

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45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454B
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454A
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454C
45464547	45464548	45464547	45464549	45464547	45464548	45464547	4546454A
45464547	45464548	45464547	45464549	45464547	45464548	45464547	454F6F45
4B454645	47454645	48454645	47454645	49454645	47454645	48454645	47454645
4A454645	47454645	48454645	47454645	49454645	47454645	48454645	47454645
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4A454645	47454645	48454645	47454645	49454645	47454645	48454645	47454645
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4C454645	47454645	48454645	47454645	49454645	47454645	48454645	47454645
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4C454645	47454645	48454645	47454645	49454645	47454645	48454645	47454645
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4A454645	47454645	[illegible]	47454645	49454645	47454645	48454645	47454645
4C454645	47454645	[illegible]	47454645	49454645	47454645	48454645	47454645
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[illegible]	[illegible]	9A9B9A9C	898A898D	898A898E	89498E89	8A892E89	8A898C9A
[illegible]	[illegible]	[illegible]	9B9A9C89	8A898B89	8A898E89	[illegible]	898B898A

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FBCBDE26 2EDBCBFB ACAB3BAC ABFBCBDE 242EDBCB FBACAB3B ACABFBCB DE252EDB
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TABLE 14. TRANSITION SEQUENCE FOR 16-BIT GRAY CODE WITH
UNIFORM DISTRIBUTION OF COLUMN CHANGES

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